

Residual Capacity Estimation for Lead–Acid Batteries Used in Automobiles by the Method of Median Internal Resistance

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Abstract The purpose of this study was to investigate the method of residual capacity estimation for lead–acid batteries used in automobiles. First, relation charts for the internal resistances of a battery at various load currents to residual capacity percentages were established, and the relation charts for all load currents were then combined to obtain the corresponding residual capacity by calculating medians. The experimental equipment included lead–acid batteries for automobiles, an electronic loader, an internal resistance tester, and test cables. The experimental procedures were discharging the battery with the electronic loader, using the internal resistance tester to record the internal resistance, voltage, and temperature of the battery, and then transmitting the data to a computer via the test cables for analysis. The experiment obtained nine sets of data, which were recorded in Excel and illustrated using charts. The medians obtained from combining the internal resistance with the residual capacity percentages were used to generate the relation charts for the internal resistances at various load currents to the residual capacity percentages. Finally, 60 Ah was used as the normal capacity to estimate the residual capacity discharging time. Furthermore, a curve-fitting approach for determining the relation equation between internal resistances and capacities was used to replace the table look-up method for residual capacity estimation. The results revealed that the estimation errors after correction were acceptable.

Keywords Curve fitting · Lead–acid battery · Residual capacity estimation · Median

Introduction

The development of science and technology has rendered batteries an indispensable power source. Electronic apparatuses such as laptops, video cameras, motor-driven wheelchairs, and mobile phones use various types of battery. Among these, lead–acid batteries offer the properties of low internal resistance, strong starting capability, simple structure, well-developed manufacturing technique, low price, and large capacity. Accordingly, lead–acid batteries are widely used in the automobile industry. The necessity for batteries required by electronic devices in modern automobiles is increasing. Ensuring that the residual capacity of the battery is always sufficient and avoiding capacity exhaustion without warning is critical. Since a driver does not know whether the residual capacity of a battery is sufficient to restart the engine after it is stopped, many drivers experience being unable to start their engines because of exhausted batteries. If this occurs at inconvenient locations or times, such as in mountain areas or late at night, it is highly problematic. Therefore, it would be considerably helpful if there were an indicator to show the residual capacity of the battery, similar to a fuel meter that indicates the fuel quantity on the instrumentation panel of an automobile. However, measuring the residual capacity of a battery is not as easy as measuring fuel quantity because it is affected by numerous factors, such as aging, charging rate, discharging rate, load, and environmental temperature. Many methods have been proposed for measuring the residual capacity of a battery. The internal resistance method estimates the residual capacity based on

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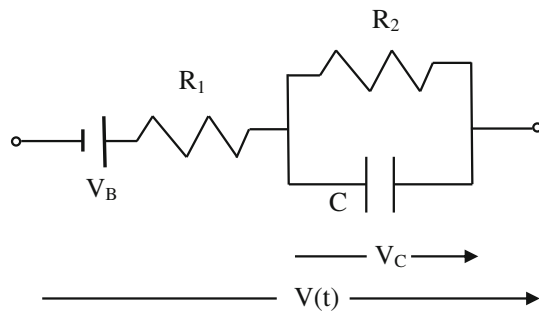


Fig. 1 Equivalent circuit of a battery

the variation of the internal resistance of a battery while the battery is discharging. In this study, a modified internal resistance technique was used to measure the residual capacity of a battery.

Regarding the measurement of residual battery capacity, the specific gravity method can directly reveal the condition of a battery. However, this method is mainly suitable for flooded lead–acid batteries. The principle of the specific gravity method is utilization of the linearity between the gravity and the battery residual capacity. We need to use a hydrometer to measure the specific gravity of the electrolyte inside the battery to estimate the residual capacity. The flooded battery is structurally unsealed and, therefore, is suitable for this method. On the other hand, the VRLA battery is structurally sealed and is difficult to measure the specific gravity of the electrolyte inside the battery [1–3]. The load-voltage method is suitable for the condition of constant load current. The terminal voltage of a battery changes abruptly if the load current varies [4]. Consequently, a larger variation of the load current results in a larger estimation error. Chan [5] recorded the terminal voltage variation of a battery while the battery was charged and discharged by a constant current to establish the equivalent circuit model of the battery. Salameh et al. [6] established a dynamic mathematic model of a battery according to the terminal voltage variation at a constant load current. In recent years, intelligent control methods, such as fuzzy control and neural networks, have been used to estimate the residual capacity of a battery based on the records of voltage, current, internal resistance, and temperature while the battery is charged and discharged [7–10].

Since the effective discharging substances in a battery decrease gradually during its discharging period, the internal resistance of the battery increases during that period [11, 12]. Figure 1 shows the equivalent circuit of a battery [13], where V_B represents the internal electromotive force (emf) of the battery, R_1 is the resistance of the metal route inside the battery, R_2 is the resistance of the electrical chemistry route inside the battery, C is the internal capacitance of the battery, and $V(t)$ represents the terminal

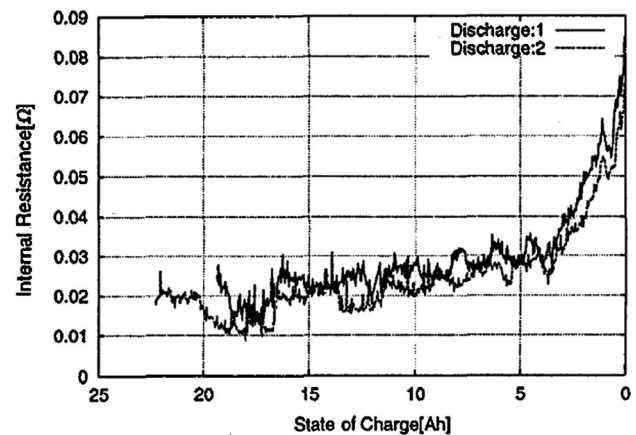


Fig. 2 The internal resistance and the residual capacity of a battery derived by Kawamura and Yanagihara

voltage of the battery. According to Fig. 1, the terminal voltage reads [14]

$$V(t) = V_B - I(R_1 + R_2) + R_2 \cdot I \cdot e^{-\frac{t}{CR_1}} - V_C \cdot e^{-\frac{t}{CR_2}}. \quad (\text{Eq 1})$$

In the steady state, Eq 1 can be simplified to

$$V(t) = V_B - I(R_1 + R_2). \quad (\text{Eq 2})$$

Accordingly, the internal resistance of the battery is derived as

$$(R_1 + R_2) = \frac{V_B - V(t)}{I} = \frac{\Delta V}{I}. \quad (\text{Eq 3})$$

Hence, the residual capacity can be estimated according to the relation between the internal resistance and the residual capacity of a battery. Figure 2 presents the relation derived by Kawamura and Yanagihara [15]. The discharging currents for the two curves in Fig. 2 are the same at 4 A, and the two curves are similar to each other. Thus, the chart was used to estimate the residual capacitance of a battery in [15].

In the next section, the characteristics of a lead–acid battery are discussed. “[Method and Equipments of Experiments](#)” section presents the method and the experimental setup of this study. The experimental results are presented and discussed in “[Experimental Results and Discussions](#)” section, and “[Conclusion](#)” section concludes the paper.

Characteristics of a Lead–Acid Battery

Structure of a Lead–Acid Battery

A lead–acid battery is a device that converts chemical energy to electrical energy through an electrochemical

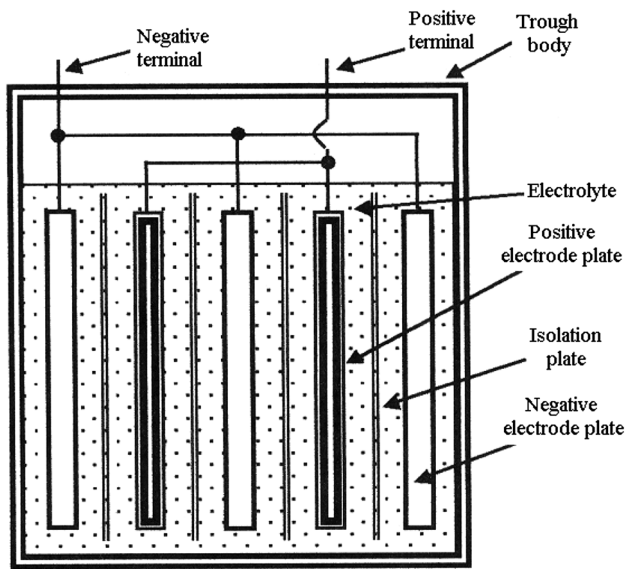


Fig. 3 Structure of a lead–acid battery

reaction; it is a recyclable and reversible dc power source. As shown in Fig. 3, the four main parts that compose a lead–acid battery are the positive and negative electrode plates, electrolyte, isolation plates, and the trough body, which are described as follows.

(1) Electrode plates

The electrode plates are composed of railing plates and active substances. The plates act as collecting electrodes, and the active substances adhere to them. The material of the active substances is lead powder, which is a compound of PbO and Pb. The lead powders are mixed into a paste and then smeared on the plates. The quantity of PbO contained in the powder is a critical performance index of a battery.

(2) Electrolyte

The sulfuric acid contained in the electrolyte conducts electricity and plays a role in the electrode reaction. The electrolyte is thus depleted gradually during the process of discharging and is also recovered in the charging process. The positive electrode of a battery produces oxygen, and the negative electrode produces hydrogen while the battery is charging. These reactions vaporize the water in the battery. Accordingly, it is necessary to replenish water to the battery to maintain its functionality.

(3) Separator

A separator is placed between the two electrode plates to prevent short circuits caused by the contact of the positive and negative electrodes. A separator should offer low resistance, high chemical stability, high acid resistance,

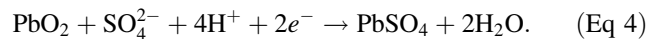
and strong antioxidation. Plates are typically fabricated from resin or rubber.

(4) Trough body

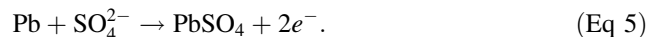
Since the inner surface of the trough contacts sulfuric acid, it should be acid resistant. The trough should also be voltage resistant, impact resistant, vibration resistant, and heat resistant to maintain the integrity of the battery. The outer part and the cover of the trough are fabricated from thermoplastic plastics through pressure-injection forming. Plastic troughs, glass troughs, and hard-rubber troughs are commonly used.

Operation of a Lead–Acid Battery

The negative and positive electrode plates are fabricated from Pb and PbO₂, respectively, and the electrolyte is H₂SO₄. The chemical reaction of a lead–acid battery is the oxidation and reduction between the positive and negative electrodes. Oxidation is a process by which a substance combines with oxygen and the substance loses electrons. Conversely, reduction is a process by which a substance deoxidizes and the substance obtains electrons. The chemical formula for the positive electrode of a discharging battery is



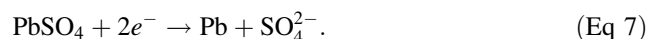
The formula for the negative electrode is



According to the formulae, both positive and negative electrodes produce lead sulfate (PbSO₄) and water is produced in the electrolyte during the discharging process. The sulfuric acid is diluted by the produced water. The chemical formula for the positive electrode of a discharging battery is



The formula for the negative electrode is



Sulfuric acid is produced in the electrolyte during the charging process, such that the concentration of the sulfuric acid increases.

Factors Influencing the Capacity of Lead–Acid Batteries

The properties of lead–acid batteries are closely related to their internal composition, and, therefore, to investigate battery performance, factors influencing the internal chemical reactions should be considered first. Five primary factors influence the residual capacity of a battery:

(1) Discharging current

When a battery discharges, its capacity varies with the load current. During high current discharge, products (large-size crystalline PbSO_4) are generated quickly near the electrodes. Over a certain output current, the products are unable to diffuse, thereby impeding the transfer of electrons and the chemical reaction.

(2) Ambient temperature

Ambient temperature exerts various effects on a discharging battery. At high temperatures, the electrochemical reactions within batteries are more active; chemical reactions are more complete, and the reaction rate is also higher. Therefore, batteries exhibit higher capacity at high temperatures. By comparison, the chemical substances in a battery are less active at low temperatures; chemical reactions are not as complete and the reaction rates are lower, thereby decreasing capacity [16].

(3) Battery aging

After a substantial number of charge–discharge cycles, the internal material structures of batteries begin to show signs of aging, such as altered electrolyte concentrations, permanent product (large-size crystalline PbSO_4) accumulation near the electrodes, electrode deformation, and deterioration of the internal materials. Consequently, long-term usage inevitably affects battery performance [17].

(4) Depth of discharge

During a long period of use, the usable capacity of a battery decreases as the number of charge–discharge cycles increases. This is called battery aging, the rate of which can be influenced by the depth of discharge.

(5) Self-discharge

Both primary batteries and secondary batteries lose charge as time passes under an open-loop condition; this is called self-discharge. In the event that the energy lost because of self-discharge is not restored within a certain period of time, the conductive materials in lead–acid batteries (PbO_2 at the positive plate and spongy Pb at the negative plate) gradually become an irreversible sulfate, PbSO_4 , which reduces the capacity of the battery.

Method and Equipments of Experiments

Method

Up to now, no existing methods of estimating residual capacity are universally applicable. Internal resistance is

currently the principal method, and after dealing with a number of technical issues, the expansibility of this method could be further facilitated. Internal resistance can be used to determine a number of battery characteristics; therefore, we employed the internal resistance method as the foundation of estimation in this study.

This method is based on the principle that the internal resistance within a battery gradually increases with a decrease in the stored energy following discharge; conversely, the internal resistance decreases as the battery is charged; therefore, estimating the status of a battery, according to internal resistance, is a means to measure residual capacity.

Under different load currents, the relation curves between internal resistances and residual capacities are different. To precisely estimate the residual capacity of the lead–acid battery in automobiles, the relation charts between different currents and internal resistances will need to be plotted, hence limited the practice of internal resistance method.

In this study, the nine commonly used currents in automobiles were used in the present study to perform the discharge experiment. Utilizing internal resistance method to plot nine curves of the relationship between internal resistance and residual capacity, then the median and interoctile deviation would be used to establish a single curve and corresponding table. This curve and table can be used to estimate the residual capacity under different currents. In addition, curve fitting was performed to establish the equation which can precisely estimate residual capacity. The proposed median internal resistance method was verified by discharge and charge for random time experiments, and the actual residual capacity was measured to validate the precision of the proposed method.

Procedures and Equipments of Experiments

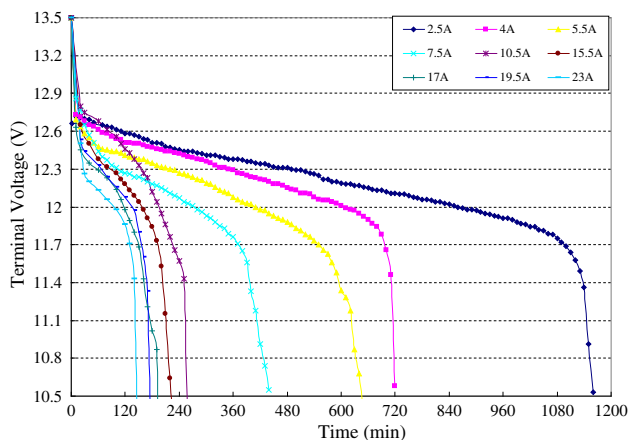
The change of the internal resistance is very tiny ($\text{m}\Omega$), and thus, the accuracy and precision of the equipments are very important. The experimental equipments include:

- (1) 12-V 60-Ah lead–acid batteries for automobiles;
- (2) an electronic loader: current range 0–60 A (resolution: 16 mA);
- (3) an internal resistance tester: measure the internal resistance, voltage, and temperature, and the range of internal resistance is 30 $\text{m}\Omega$ (resolution: 10 $\mu\Omega$).

The experimental procedures are discharging the battery with the electronic loader, using the internal resistance tester to record the internal resistance, voltage, and temperature of the battery, and then transmitting the data to the computer for analysis using the test cables.

Table 1 Various load currents of automobiles [18]

Category of load	Load current, A
Ignition switch	2.5
Side lights	7.5
Head lamps	16.0
Parking lights	10.5
Turning indicator	2.5–6.5
Air conditioning (fan—weak)	17.0
Air conditioning (fan—middle)	19.5
Air conditioning (fan—strong)	28.0
Tail lamps	15.5
Wipers	3.5–5.5
Recorder and player	3.0
Power window	7.0
Cigarette lighter	10.5
Interior lights	2.0
Fog lamps	15.5
Starter (summer)	100–250
Starter (winter)	150–400

**Fig. 4** The relationship between terminal voltage and discharge time

Experimental Results and Discussions

Proposed Estimation Method of Median Internal Resistance

We selected nine load currents commonly used in cars as the discharge currents in our experiment (Table 1) [18], namely, 2.5, 4, 5.5, 7.5, 10.5, 15.5, 17, 19.5, and 23 A. To discharge commenced when the terminal voltage was 13.5 V (full capacity voltage) and concluded when the terminal voltage reached 10.5 V (cutoff voltage). Data were retrieved every ten minutes. The terminal voltage-discharge time curve is exhibited in Fig. 4; the relationship between internal resistance and discharge time is shown in Fig. 5.

The minimum values of the internal resistance curves in Fig. 5 were set as full capacity (100%); the capacities at cutoff were set as zero capacity (0%). Figure 6 presents the results of Fig. 5 with time converted into the percentage of residual capacity. As shown in the figure, the nine internal resistance values corresponding to 0% residual capacity form a data series. The median of this series equals 14.9 m Ω . Similarly, we obtained the median internal resistance values corresponding to 10, 20,..., and 100% residual capacity. The results are listed in Table 2.

The interoctile deviation was applied to find the residual capacity of the nearby two median internal resistance. The corresponding interoctile deviation of 0, 10, and 20–100% residual capacity was calculated and is shown in Table 2. The relationship between median internal resistance and corresponding deviation of residual capacity percentage is shown in Fig. 7. Therefore, once the internal resistance was known, the corresponding residual capacity could be calculated by Fig. 7 and this is the proposed median internal method.

Validation Experiment I (Discharge vs. Random Time)

To verify the accuracy of the median internal resistance method, experiments were conducted using seven load currents other than those employed above: 2.5, 6, 8, 13, 16, 21, and 23 A. Fully charged batteries (13.5 V) were, respectively, discharged at the seven discharge currents for random periods (10, 5, 5, 2, 1, 1, and 1 h). Discharge was continued until cutoff voltage (10.5 V) was reached, the time which was recorded.

For example, with a discharge current of 6 A, a battery was charged to full capacity and we recorded its internal resistance. After 5 h of discharge, the internal resistance reached 5.89 m Ω . According to Fig. 7, the residual capacity of the battery was estimated to be 29%. The estimated residual discharge time was calculated by the estimated percentage times the normal capacity (60 Ah) and divided by the discharge currents (6 A). The battery was continued to be discharged, and we measured data every 30 min until cutoff voltage. The results in Table 3 show that the battery continued to discharge for another 3 h and this is the actual residual discharge time. The verification results from the seven discharge currents and errors are presented in Table 4.

Validation Experiment II (Charge vs. Random Time)

In this experiment, each of the batteries was discharged until they reached cutoff voltage (10.5 V) and we then charged each for a random period of time. The internal resistance values of each were measured, following which

Fig. 5 The relationship between internal resistance and discharge time

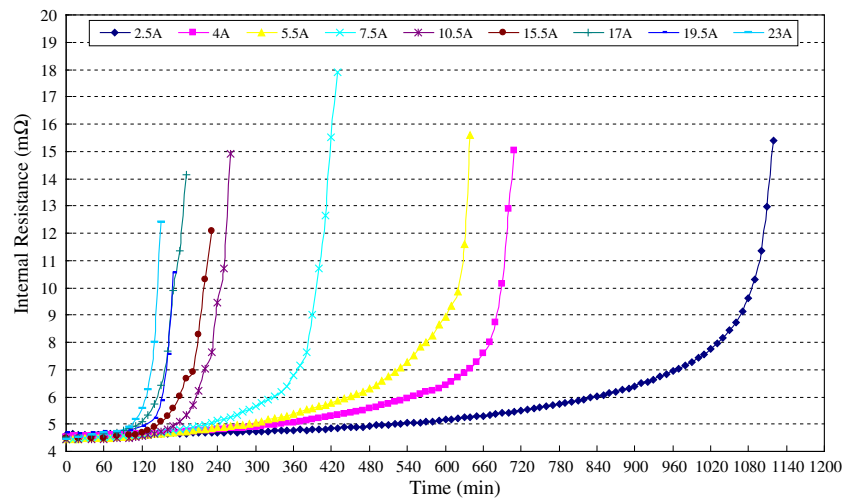


Fig. 6 The relationship between internal resistance and the residual capacity percentages of different load currents

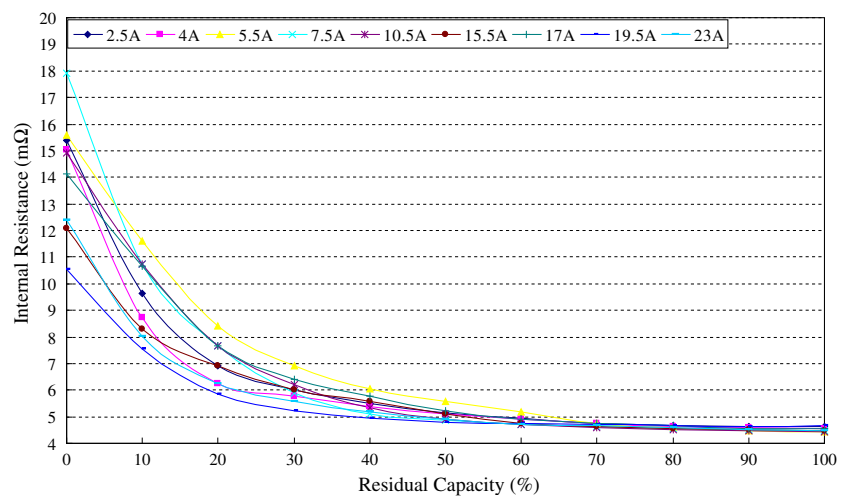


Table 2 The median internal resistances and corresponding interoctile deviation of residual capacity percentages

Residual capacity, %	Median internal resistance, mΩ	Interoctile, mΩ
100	4.47	±0.02
90	4.52	±0.0225
80	4.6	±0.0325
70	4.71	±0.035
60	4.8	±0.05
50	5.11	±0.065
40	5.38	±0.0975
30	6.01	±0.11
20	6.93	±0.3475
10	9.62	±0.605
0	14.9	±0.745

the batteries were discharged at five load currents (2.5, 9, 12, 14, and 23 A). In this experiment, we verified the residual capacity following random charging periods.

For example, with a discharge current of 9 A, a battery was charged for a random period of time and we recorded its internal resistance as 5.88 mΩ. By the methods described in the previous section, the estimated discharge time and actual discharge time were measured and verification results are shown in Table 5.

Curve Fitting

Finally, curve fitting was employed to simulate the data curve obtained using the median internal resistance approach in this study (Fig. 7). Curve fitting is an essential step in data analysis, the objective of which is to construct a mathematical model using a limited number of sample points. The resulting mathematical model can be used to conduct further prediction and analysis. In this study, MATLAB was used to perform curve fitting using a polynomial equation. First, the data in Table 2 were substituted into the following equation to derive the optimal equation:

Fig. 7 The relationship between internal resistance and the residual capacity percentages by median internal method

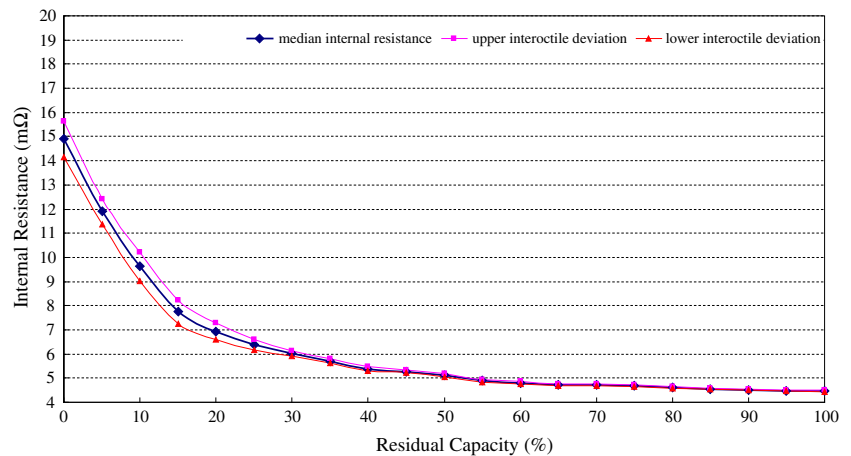


Table 3 The discharge experiment data: discharge current (6 A) for a random period

Discharge time, h	Internal resistance, mΩ	Terminal voltage, V
Began to discharge	4.48	13.50
5	5.89	12.15
5.5	6.04	12.08
6	6.27	12.08
6.5	6.71	11.94
7	7.78	11.72
7.5	10.01	11.08
8	14.33	10.48

Table 4 The results of verification experiment (I) and curve fitting: residual discharge time and errors

Discharge current, A	Estimated residual discharge time and percentage of error, %	Actual residual discharge time, h	Curve-fitting results and percentage of error, %
2.5	2.8 h (6.67%)	3	3.209 h (6.67%)
6	2.917 h (2.78%)	3	2.857 h (4.44%)
8	2.187 h (9.16%)	2	1.995 h (0%)
13	1.884 h (5.83%)	2	1.843 h (7.5%)
16	0.875 h (11.67%)	1	0.979 h (1.67%)
21	1 h (0%)	1	1.036 h (3.33%)
23	0.609 h (8.75%)	0.667	0.679 h (2.49%)

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 + a_7x^7, \quad (\text{Eq } 8)$$

where y is the internal resistance of the battery, and x is the percentage of residual capacity in the battery; $a_0, a_1, a_2, a_3, a_4, a_5, a_6$, and a_7 are the parameters of the equation. The resulting parameters of the simulation are shown in Table 6. Figure 8 exhibits the relationship curve of the simulation results and the median internal resistance

Table 5 The results of verification experiment (II) and curve fitting: residual discharge time and errors

Discharge current, A	Estimated residual discharge time and percentage of error, %	Actual residual discharge time, h	Curve-fitting results and percentage of error, %
2.5	2.8 h (6.67%)	2.5	2.365 h (5.33%)
9	1.94 h (3.33%)	2	1.914 h (4.16%)
12	2.042 h (2.5%)	2	1.931 h (3.33%)
14	1 h (0%)	1	0.923 h (6.67%)
23	0.457 h (8.67%)	0.5	0.539 h (7.67%)

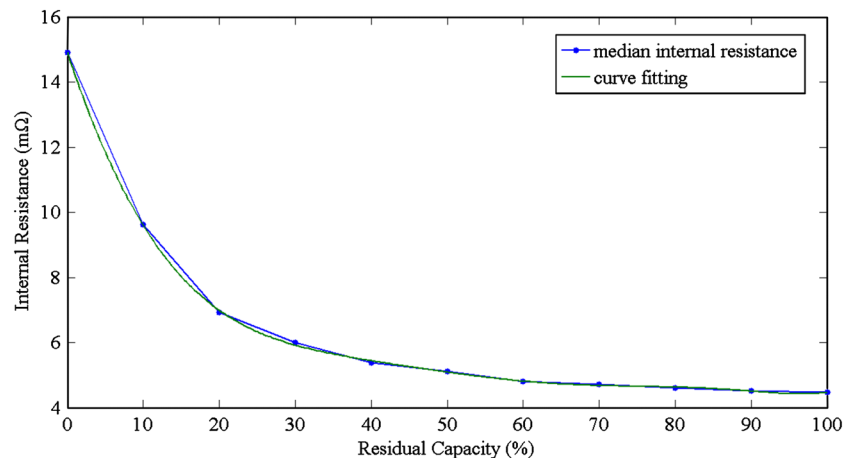
Table 6 The parameters of the curve-fitting equation

Parameters	Values
a_0	14.9317
a_1	−0.6991
a_2	0.0156
a_3	1.5676×10^{-4}
a_4	-1.3555×10^{-5}
a_5	2.4677×10^{-7}
a_6	-1.9323×10^{-9}
a_7	5.6727×10^{-12}

values. The results of the two verification experiments were substituted into Eq 8 to calculate the percentage of residual capacity and infer the degree of error. The results are shown in Tables 4 and 5.

After comparing the residual capacity percentage calculated by curve fitting and table look-up method, the estimation error of calculating residual discharge time was acceptable. Although curve fitting increased the error percentage slightly, it also reduced the magnitude of error in circumstances of greater error. Furthermore, all errors were less than 8%.

Fig. 8 The relationship between internal resistance and the residual capacity percentages by curve fitting



Conclusion

This paper proposes that the residual capacity of lead–acid batteries used in automobiles can be precisely estimated using the median internal resistance method. According to the results of the validation experiment, in which batteries were discharged and charged for random times, different currents were observed to influence the precision of residual capacity estimation, with error less than 12%. Furthermore, the residual capacity was estimated using the proposed curve-fitting equation, and the error was less than 8%. This degree of accuracy demonstrates the applicability of this method for a range of load currents. A device capable of indicating residual capacity can help to prevent permanent battery damage caused by over-discharge as well as situations in which engines are unable to start because of low battery capacity.

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